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Putting the Geology Back Into Earth Models

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New digital methods for data capture can now provide photorealistic, spatially precise, and geometrically accurate three-dimensional (3-D) models of rocks exposed at the Earth's surface [*Xu et al.*, 2000; *Pringle et al.*, 2001; *Clegg et al.*, 2005]. These "virtual outcrops" have the potential to create a new form of laboratory-based teaching aids for geoscience students, to help address accessibility issues in fieldwork, and generally to improve public awareness of the spectacular nature of geologic exposures from remote locations worldwide.

This article addresses how virtual outcrops can provide calibration, or a quantitative "reality check," for a new generation of high-resolution predictive models for the Earth's subsurface.

Geological architectures span at least 12 orders of magnitude in length (Figure 1), from individual microstructures to lithospheric plates. Traditional paper-based geological mapping and fieldwork techniques have not been able to capture accurately the geospatial properties of mesoscale (0.0001 to 100 meters) features in surface outcrops. In addition, geophysical imaging of the subsurface is poor at these scales.

This lack of fine-scale spatial precision has meant that the superbly detailed lithological units and structures seen in surface outcrops have not been integrated directly into predictive numerical and analogue models.

As a result, models created to simulate mesoscale geology are currently not well calibrated to natural data sets (Figure 1), and it is therefore difficult to demonstrate even partial confirmation of predictive 3-D models [*Oreskes et al.*, 1994]. This creates significant problems for industrial users interested in the extraction or storage of fluids in subsurface reservoirs because accurate predictions of these processes rely on a complete 3-D understanding of the subsurface mesoscale geology.

Digital Fieldwork Technologies

Terrestrial laser scanners and Real Time Kinematic (RTK) (a system whereby Global Positioning System (GPS) positions are corrected in real time from a reference receiver) GPS units are the principal tools used to capture digital data from surface outcrops (Figure 2). Automatic data collection involves scanning the outcrop surface with a laser to record the topography in a series of x,y,z coordinates, known as a "point cloud" (J. A. Bellian et al., http://www.searchanddiscovery.net/documents/beg3d/index.htm; S. Ahlgren and J. Holmlund, http://www.searchand discovery.net/documents/geophysical/2003/ahlgren/index.htm). Using built-in digital cameras, the newest laser scanners collect spatially registered photographs that allow the software to color the point cloud to match the outcrop and produce a photorealistic 3-D image [*Clegg et al.*, 2005; *McCaffrey et al.*, 2005].

Laser scanning produces large volumes of data rapidly (up to 12,000 points per second), but the range of attributes is limited, and laser scanning works best on cliff sections or in mines and quarries where the scanner can be placed directly in front of the outcrop. With

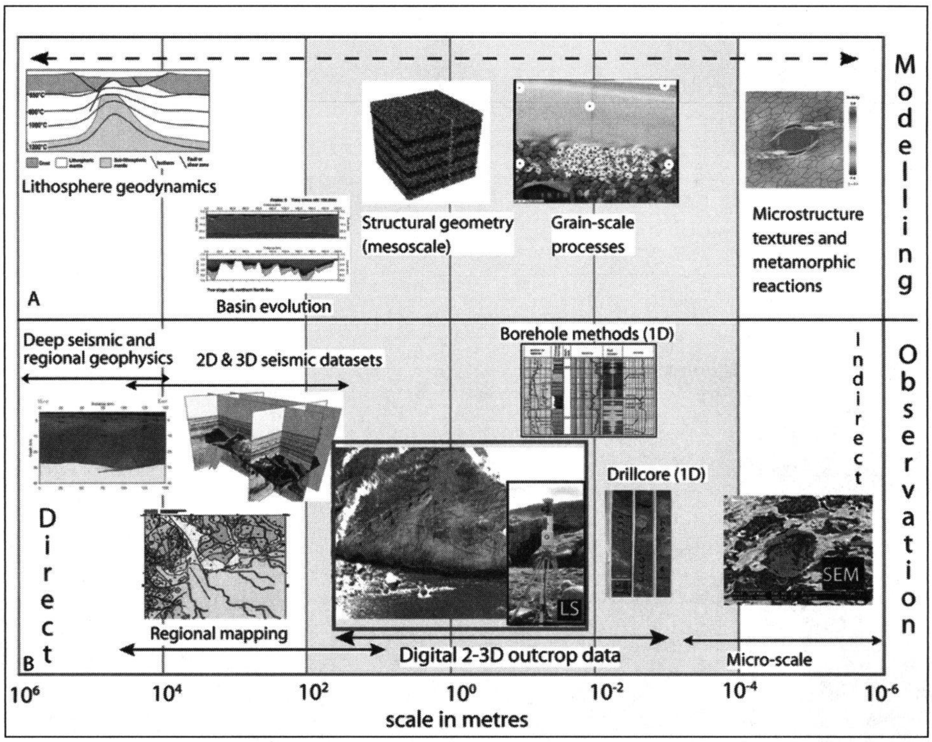

Fig. 1. (a) Typical two- and three-dimensional (2-D and 3-D) numerical (finite element, finite difference, discrete element) and analogue (sand box, flume tanks, silicone putty) models used to investigate Earth system behavior over 12 orders of magnitude in scale range. Models generally are scaled to match the process being investigated, but their coverage rarely exceeds three orders of magnitude in range. (b) Directly or indirectly observed/measured data using a range of methods at different scales. Subsurface fluid flow is most likely influenced by processes and structure in the mesoscale range 0.0001 to 100 meters (shaded blue in diagram). At this scale range, observational data are limited to one-dimensional borehole and drill-core, and 2-D and 3-D rock outcrops. New digital fieldwork methods (red box on diagram; see also text) provide georeferenced field data to calibrate the spatial geometry of model predictions and provide high-resolution (millimeter-scale) images of the Earth's 3-D surface and subsurface architecture. Abbreviations are LS, laser scanner; SEM, scanning electron microscopy. Original color image appears at the back of this volume.

BY K. MCCAFFREY, R. HOLDSWORTH, J. IMBER, P. CLEGG, N. DE PAOLA, R. JONES, R. HOBBS, N. HOLLIMAN, AND I. TRINKS

RTK GPS data collection, any measurable attribute (surface dip, strike, lithology) can be recorded together with the spatial coordinates at a user-controlled sample spacing down to approximately five centimeters.

The efficiency of point cloud data collection is determined by the speed at which the attribute is measured, but this is unlikely to be faster than one point per second.

As the method is GPS-based, it works best on sub-horizontal outcrop surfaces with an unobstructed view of the sky. Topographic surfaces fitted to the point cloud data are then textured using the digital photographs to provide a photo-realistic finish (Figure 2). The resultant 3-D virtual outcrop can be interpreted onscreen and further explored using visualization systems that use stereoscopic methods to allow the user to apparently immerse themselves within the data.

An additional advantage is that these outcrop-scale data can be easily integrated into a single standardized database (e.g., a 3-D geographical information system) and combined with other geological or geophysical data sets collected across a range of scales [*Jones et al.*, 2005].

The key advantages these methods have over traditional mapping are that every feature is precisely located in space and the efficiency of data acquisition is significantly increased (Figure 2).

The precise spatial location of every observation means that the predictions and interpretations made by one geoscientist are easily tested by another in the laboratory or, ultimately, back at the outcrop. Arguably, 3-D models constructed in this way are more true to reality than abstract cartoons sketched out by geoscientists using traditional paper-based methods [*Jones et al.*, 2004].

Calibration of Numerical Models

This article here illustrates how these new digital data capture techniques can calibrate predictive models, by focusing on two examples of RTK GPS data collected from the Northumberland Basin, United Kingdom (Figure 3).

In the first example, the morphology of natural folded bedding surfaces may be compared and used to directly calibrate mesoscale models of fault-propagation folds [*Cristallini and Allmendinger*, 2001] (Figures 3a, 3b, and 3c, top). In this case, around 4500 data points were collected over a decimeter-scale folded sandstone bedding surface with an average sample spacing of 10 centimeters. The folds were likely formed as fault-propagation folds related to regional oblique tectonics (see *De Paola et al.* [2005] for details).

The second example illustrates how the authors of this article used RTK GPS equipment to map a segmented, outcrop-scale normal fault system [maximum throw (vertical separation across fault) <0.3 meter], and compared the mapped geometries with the results of 3-D geomechanical (discrete element) models of fault relay zones [*Imber et al.*, 2004]. The new digital mapping techniques can be used to collect data from mesoscale fault systems quickly and accurately and to quantify the way in which displacement is transferred between individual fault segments across small (centimeter-scale) relay zones.

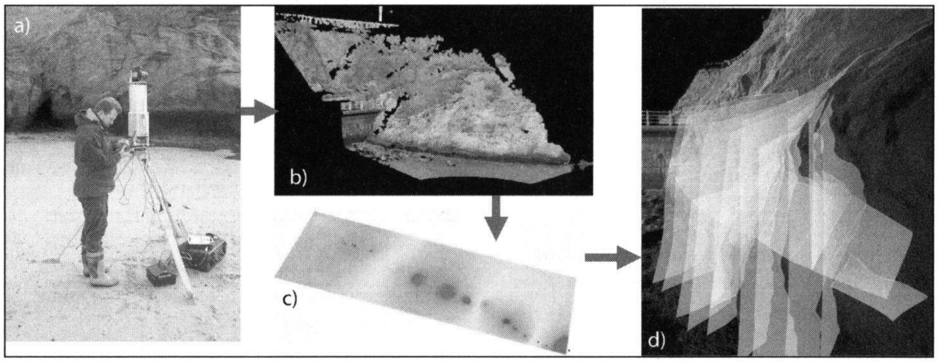

Fig. 2. (a) Terrestrial laser scanning of dune cross-bedded Permian sandstones at Cullercoats, northeastern England. The sandstones contain a heterogeneous and complex system of deformation bands that developed during movement on a Paleozoic to Mesozoic basin-bounding fault (90 Fathom Fault) [see De Paola et al., *2005]. The example is typical of a sandstone oil/gas reservoir rock that might be poorly imaged in the subsurface. Over a period of two days, approximately 200 meters of outcrop were scanned and photographed, producing a combined data set of around nine million data points. (b) The data shown represent a virtual outcrop generated from a single scanning location with a lateral point density of about two centimeters on the outcrop and consisting of approximately 850,000 scan points. (c and d) Precisely located centimeter-scale fault planes mapped in the 3-D virtual environment that can be used to condition models of subsurface mesoscale structure. Original color image appears at the back of this volume.*

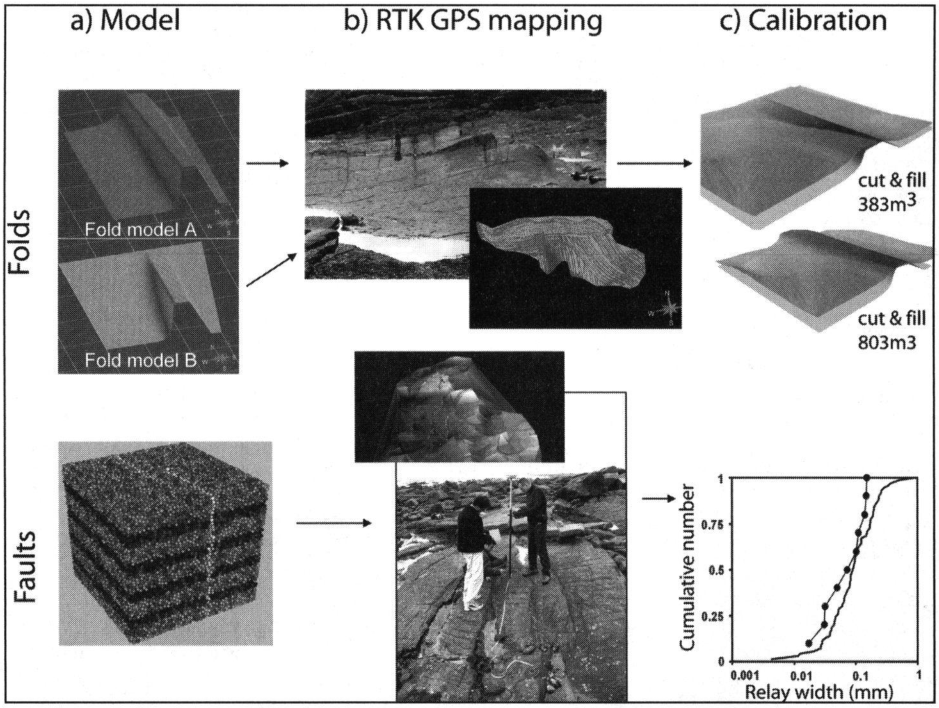

Fig. 3. (a) Numerical models of mesoscale structures. Top shows 3-D kinematic models of fault-propagation folds utilizing the trishear mechanism [from Cristallini and Allmendinger, *2001]. Bottom shows a geomechanical (discrete element) model to predict the growth and breaching of mesoscale relay zones. (b) Top shows decimeter-scale folds in outcrop at Howick, Northumberland Basin, northeastern England [see* De Paola et al., *2005], captured using RTK GPS with x, y, z data points and fitted surface corresponding to the bedding plane. Bottom shows normal fault system exposed at Lamberton, southeastern Scotland, looking south, and Real Time Kinematic Global Positioning System model of the Lamberton fault system. Data points collected along the fault-horizon cutoffs are colored. Additional data were collected in order to construct a topographic model of the faulted sandstone bed (gray triangulated surface). (c). Top shows fold shape quantitatively compared with modeled surfaces by cut-and-fill estimation enabling calibration of model parameters. Bottom shows normalized cumulative frequency of relay breaching strains for natural (solid line) and model (dots) relay zones after* Imber et al. *[2004]. Original color image appears at the back of this volume.*

In the second example, approximately 1000 data points were collected at 0.2-meter spacing along the intersections (cutoffs) between a well-exposed sandstone bed and the fault planes (Figure 3b, bottom). The natural examples measured and those predicted by the numerical modeling correspond well (Figure 3c, bottom).

These new RTK GPS-derived 3-D models provide the spatial precision that enables the construction of predictive models of relay structure geometry and their fluid transport properties at the meter scale. The spatial resolution here is improved by at least two orders of magnitude compared with that used in current models.

These examples show how digital data sets provide a 3-D geological model that can be used to calibrate mesoscale numerical and analogue models in the same way that geophysical data sets (seismic reflection, gravity, and magnetics) are used to constrain lithosphere geodynamic and basin models (Figure 1).

The fundamental challenge for these new methods will be to deliver improved fine-scale geological constraint on predictive geomechanical models, which would allow the fine tuning of stochastic simulations of "subseismic resolution" structure for use in models of the subsurface (e.g., oil reservoirs). These methods may also provide spatial calibrations for geodynamic models since increasing computer performance will soon allow model resolution to approach the mesoscale.

The authors suggest that the emergence of these digital methodologies represents a paradigm shift in how field-based data-gathering will be carried out and the manner in which the results will be integrated into modern Earth science investigations.

Acknowledgments

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Celebrating the Physics in Geophysics

PAGES 461, 467

The United Nations Educational, Scientific and Cultural Organization (UNESCO) declared 2005 the "World Year of Physics" in celebration of the centennial of Einstein's annus mirabilis when, as junior clerk at the Swiss Patent Office in Berne, he published three papers that changed physics forever by (1) introducing Special Relativity and demonstrating the equivalence of mass and energy ($E = mc^2$), (2) explaining the photoelectric effect with Planck's then-still-new-and-controversial concept of light quanta ($E = h\nu$), and (3) investigating the macroscopic phenomenon of Brownian motion using Boltzmann's molecular dynamics ($E = kT$), still far from fully accepted at the time.

The celebration of Einstein's work in physics inspires the reflection on the status of geophysics and its relationship with physics, in particular with respect to great discoveries.

Like surprisingly many others in AGU, the authors of this article are trained as physicists, work primarily in geophysics, and enjoy thoroughly their research activity in atmospheric and solid Earth science. The following article takes a broad view to examine the past and future of the intricate and evolving relation between geoscience and physics.

By A. B. Davis and D. Sornette

Successful Applications of Fundamental Physics to the Geosciences

Prefacing his *Principles of Philosophy*, the seventeenth-century French philosopher, mathematician, and physicist René Descartes described philosophy as a tree rooted in metaphysics, with physics as its trunk and other scientific disciplines such as mechanics or medicine its branches. This "tree of philosophy" is an extreme version of the general perception that physics is the queen of sciences and that all others are essentially different flavors of applied physics.

Phil Anderson, condensed-matter physicist and Nobel laureate, contended in his 1972 essay "More is different" [*Anderson,* 1972] that particle physics and indeed reductionism have only a limited ability to explain the world. He argued that reality is structured hierarchically, each level being independent, to some extent, of levels above and below: "At each stage, entirely new laws, concepts and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one" (p. 393). Anderson noted, "Psychology is not applied biology, nor is biology applied chemistry" (p. 393).

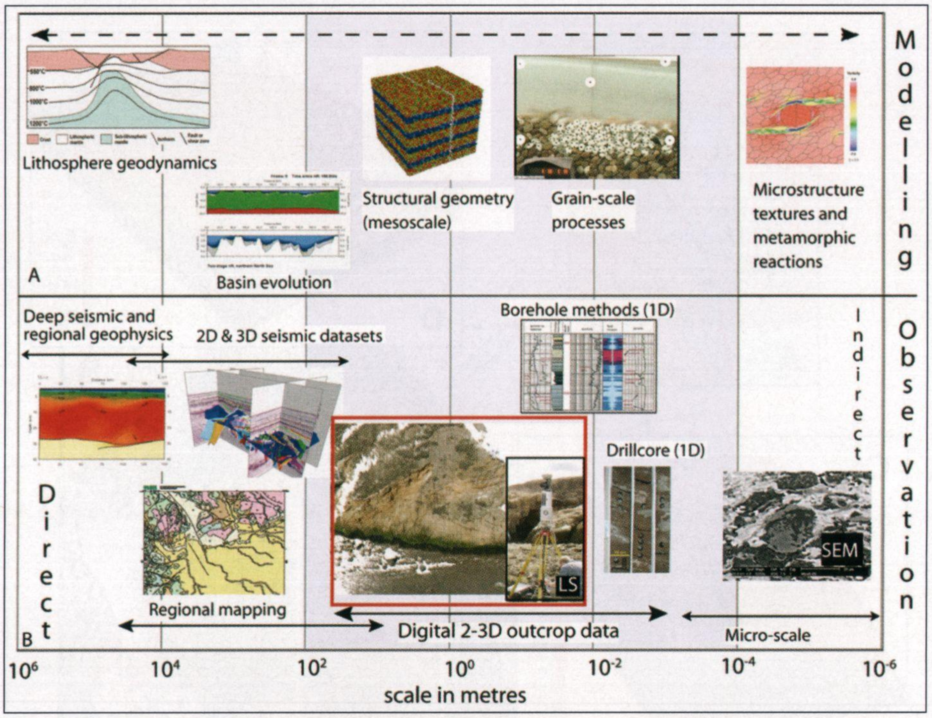
Indeed, geophysics, far from being just another field of applied physics, has driven physics itself to innovate in deep and lasting ways.

However, geophysical research is generally perceived as using basic scientific principles to explain observations while hypothesizing theories on the cause of still-unresolved structures and dynamics.

For example, in 1752, Benjamin Franklin performed his famous kite-flying experiment, establishing that lightning is a naturally occurring electric spark. In the nineteenth century, John Tyndall's investigation of the radiative properties of gases contributed greatly to the understanding of how gases affect the heating and cooling of the atmosphere. Svante Arrhenius, who received the Nobel Prize in chemistry in 1903, presented groundbreaking work to the Stockholm Physical Society in 1895 on the influence of "carbonic acid" (as he referred to carbon dioxide) in the air upon the temperature of the ground, a phenomenon still debated by Earth scientists and the broader community.

Early in the twentieth century, Serbian astrophysicist Milutin Milankovitch developed a mathematical theory of climate based on seasonal and latitudinal variations of solar radiation from varying Earth-Sun geometry (orbital eccentricity, obliquity, and precession). This theory still stimulates research in mathematics and physics, both applied and fundamental.

Pioneering an interdisciplinary approach, Alfred Wegener wrote in 1915 one of the most influential and controversial books in the history of science, *The Origin of Continents and Oceans*, therein offering his theory of drifting



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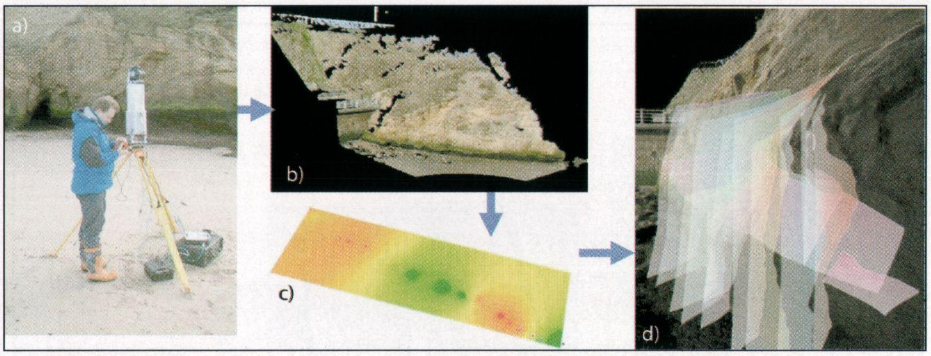

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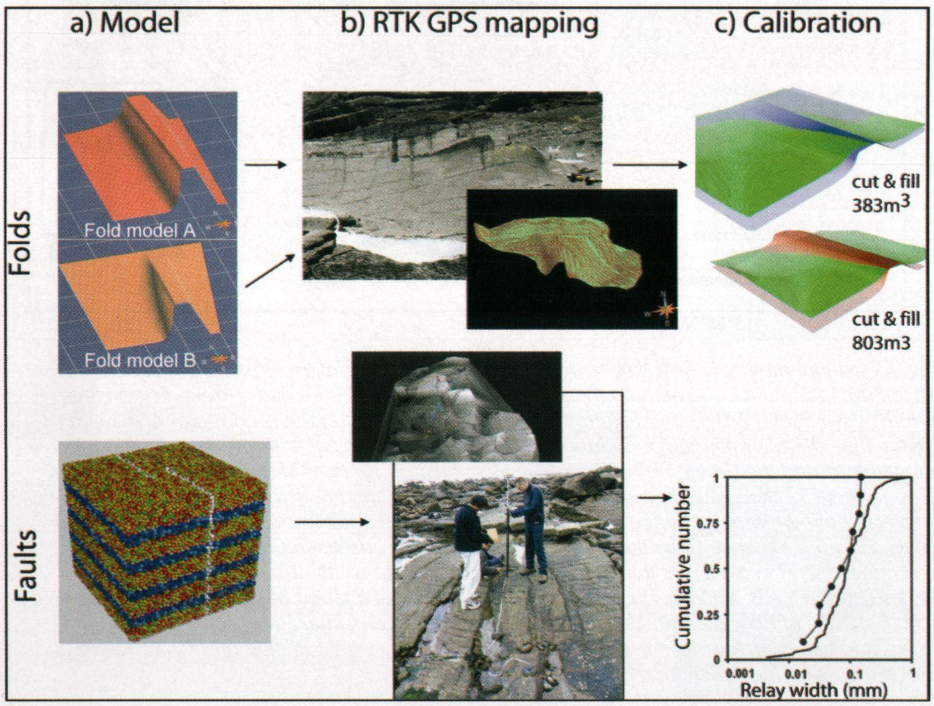

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